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ROTATING DISCONTINUITIES IN THE SOLAR WIND

by

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Conditions for rotating discontinuities in plasma with anisotropic pressure are studied on the basis of the most simple closed system of hydrodynamic equations for rarified plasma. It was ascertained that for anisotropic rotating discontinuities, differing from isotropic ones, intermittent changes in the module of the magnetic field H are possible, and tangential components of H on the front are always colinear. Through analysis of simultaneous plasma and magnetic data, it was shown that 10 out of 11 "large discontinuities of velocity" observed by "Explorer-34" in 1967 may be considered rotating discontinuities and not of the tangential type since the specific conditions for rotating discontinuities $H_n \{v_t\} = \{H_t\} v_n$, connecting jumps in the tangential components of solar wind flux velocity with the interplanetary magnetic field are satisfied in them.

Analyses [1-3] of sounding observations on solar wind discontinuities were conducted in proximity to a magnet through hydrodynamics with isotropic pressure. Aside from this, the anisotropia of proton and electron temperatures was discovered [4-6] in a number of cosmic experiments. In light of these experiments, it is clear that the stricter approach to interpretation of solar wind discontinuity observations is an approach based on results of anisotropic magnetohydrodynamics. The first step in this direction was attainment in [7] of conditions for strong anisotropic discontinuities. Written in a coordinate system in which the front of the discontinuity is stabilized, these conditions have the following appearance:

$$
\begin{gathered}
\{H_n\} = 0, \ \{\rho v_n\} = 0, \\
\{\rho v_n^2 + p_\perp + H_t^2/8\pi + \lambda H_n^2/4\pi\} = 0, \\
\{\rho v_n \mathrm{v}_t - (1-\lambda) H_n \mathrm{H}_t/4\pi\} = 0, \\
\{H_n \mathrm{v}_t\} = \{\mathrm{H}_t v_n\}, \ \{p_\perp v_n/H\} = 0, \\
\{w v_n + v_n(p_\perp + H^2/8\pi) - (1-\lambda) H_n \mathrm{H}\mathrm{v}/4\pi\} = 0,
\end{gathered} \tag{1}
$$

where ρ, v, H -- density, velocity and magnetic field (indices n and t relate to normal and tangential components); $\lambda = (p_\parallel - p_\perp)4\pi/H^2$ ($p_{\parallel,\perp}$ -- pressure along the field); $w = 1/2[3p_\perp + \rho v^2 + (1-\lambda)H^2/4\pi]$ -- energy density; the shaped brackets indicate that the difference in values along both sides of the front is used.

In the future we will be interested in discontinuities with a non-zero mass flux and constant density. In normal magnetohydrodynamics, rotating discontinuities are single discontinuities satisfying the noted limits of flux and density [8] and they may therefore be arbitrarily called anisotropic discontinuities with $\rho_1 v_{1n} = \rho_2 v_{2n} \neq 0$ and $\rho_1 = \rho_2$ -- anisotropic rotating discontinuities. The conditions of (1) in this case are somewhat simplified

$$
\{H_n\} = 0, \ \rho_1 v_{1n} = \rho_2 v_{2n} \neq 0, \ \rho_1 = \rho_2 = \rho, \ v_{1n} = v_{2n} = v_n, \tag{2}
$$
$$
\{p_\perp + H_t^2/8\pi + \lambda H_n^2/4\pi\} = 0, \tag{2a}
$$
$$
\{\rho v_n \mathrm{v}_t - (1-\lambda) H_n \mathrm{H}_t/4\pi\} = 0, \tag{2b}
$$
$$
H_n \{\mathrm{v}_t\} = \{\mathrm{H}_t\} v_n, \tag{2c}
$$
$$
\{p_\perp/H\} = 0, \tag{2d}
$$
$$
\{w v_n + v_n (p_\perp + H^2/8\pi) - (1-\lambda) H_n \mathrm{H}\mathrm{v}/4\pi\} = 0.
$$

Eliminating $\{\mathrm{v}_t\}$ from (2b) and (2c), we obtain

$$
\{[\rho v_n^2/H_n - (1-\lambda) H_n/4\pi]\mathrm{H}_t\} = 0. \tag{3}
$$

If it is allowed that $p_{\perp 1} = p_{\perp 2}$, then due to (2) and (2d) we have $H_1 = H_2$ and $H_{1t} = H_{2t}$, and on the basis of (2a) $p_{1\parallel} = p_{2\parallel}$. In sum, (3) will take the form

$$
[\rho v_n^2/H_n - (1-\lambda) H_n/4\pi] \ \{\mathrm{H}_t\} = 0, \tag{4}
$$

and inasmuch as $\{H_t\} \neq 0$, movement velocity about such a discontinuity along the plasma

$$v_n = \pm H_n \left[(1-\lambda)/4\pi\rho\right]^{1/2}. \tag{5}$$

A discontinuity with the noted properties is taken in [7] as an example of an anisotropic rotating discontinuity. This discontinuity, due to $\{H_t\} \neq 0$ and the continuity of H allows an arbitrary jump of direction H_t -- rotation of the field around H_n during passage through the discontinuity. In this manner the behavior of a field at this discontinuity is the same as at an isotropic rotating discontinuity, but velocity of propagation somewhat differs (in the isotropic case, $\lambda = 0$ and $v_n = \pm H_n/(4\pi\rho)^{1/2}$). In the general case however, if $p_{1\perp} \neq p_{2\perp}$, then in accordance with (2) and (2d), $H_1 \neq H_2$, $H_{1t} \neq H_{2t}$ and (3) describes a new type of anisotropic rotating discontinuity with essentially different behavior of the magnetic field. Thus, in a general case, from (3) we have

$$H_{t2} = \frac{4\pi\rho v_n^2 - (1-\lambda_1) H_n^2}{4\pi\rho v_n^2 - (1-\lambda_2) H_n^2} H_{t1}, \tag{6}$$

which is to say H_{2t} and H_{1t} are colinear and the field does not experience voluntary rotation but changes according to an absolute value and direction, always remaining in a plane perpendicular to the front and constituting $H_{1,2}$. If the multiplier before H_{t1} in (6) is less than zero, the direction of the tangential component of the field changes by 180° during passage through the discontinuity.

From (3) we have the movement velocity of the discontinuity along the plasma

$$v_n = \pm H_n \left[\frac{(1-\lambda_2) H_{2t} - (1-\lambda_1) H_{1t}}{4\pi\rho (H_{t2} - H_{t1})}\right]^{1/2}. \tag{7}$$

which with $\lambda_1 = \lambda_2 = \lambda$ gives the case selected in [7], and with $\lambda_1 = \lambda_2 = 0$ leads to the expression for velocity of an isotropic rotating discontinuity [8].

This property of anisotropic rotating discontinuities should be considered during interpretation of solar wind discontinuities. Usually, information on H, v, concentrations of n and effective temperatures of protons T_p are published. It is interesting that even according to these data, some observed discontinuities manifest the inherent signs of anisotropic rotating discontinuities. We will show that 10 out of 11 (see table) "large discontinuities in velocity" observed on "Explorer-34" in 1967 [9] may relate to rotating discontinuities. The noted discontinuities are not shock waves according to the character of change in v or n or T_p, depending on the actual case. The central changes in velocity eliminate the possibility of their interpretation as contact discontinuities. (The author [9] interprets these discontinuities as tangential ones.) Besides this, it has become apparent that they satisfy the specific conditions for rotating discontinuities connecting jumps in v_t with a jump in H_t.

Thus, from (2) we have $\{\mathbf{v}_t\} = \{\mathbf{H}_t\} v_n / H_n,$

where v_n is determined by (7). The first measurements [4-6] show that the degree of anisotropia of plasma pressure in the cosmic surroundings of Earth $p_{\parallel}/p_{\perp}$ usually comprise 1-2. In the limit for the solar wind with almost isotropic pressure from (7) we have $v_n \approx H_n/(4\pi\rho)^{1/2}$. Inasmuch as the reviewed data does not contain information on pressure components, we evaluate jumps in velocity of the discontinuities according to

$$\mathbf{v}_{t2} - \mathbf{v}_{t1} = \Delta \mathbf{v}_t \approx (\mathbf{H}_{t2} - \mathbf{H}_{t1})/\sqrt{4\pi\rho}, \quad \Delta v_t \approx (H_{t2} - H_{t1})/\sqrt{4\pi\rho}, \tag{8}$$

where the latter expression is accomplished in the form of (6) -- colinearity of H_{t1} and H_{t2} for anisotropic rotating discontinuities.

In the solar eclipse coordinates, rotation behind the front $v_2 = v_1 + \Delta v_t$ according to the module is equal to

$$v_2 = [(-v_1 \cos\beta + l_t \Delta v_t)^2 + (v_1 \sin\beta + m_t \Delta v_t)^2 + (n_t \Delta v_t)^2]^{1/2}, \qquad (9)$$

where for evaluation, v_1 has been taken as directed radially from the sun, $\beta \approx 4°$ is the angle of aberration of the wind; guiding cosines of magnetic field disturbance [2] $h = H_2 - H_1$ are equal to

$$\begin{gathered} l_t = (H_2 l_2 - H_1 l_1)/A,\ m_t = (H_2 m_2 - H_1 m_1)/A,\ n_t = (H_2 n_2 - H_1 n_1)/A, \\ A = [(H_2 l_2 - H_1 l_1)^2 + (H_2 m_2 - H_1 m_1)^2 + (H_2 n_2 - H_1 n_1)^2]^{1/2}, \\ l_{1,2} = \cos\theta_{1,2} \cos\varphi_{1,2},\ m_{1,2} = \cos\theta_{1,2} \sin\varphi_{1,2},\ n_{1,2} = \sin\theta_{1,2} \end{gathered} \qquad (10)$$

(θ, ϕ -- angles determining orientation of $H_{1,2}$ in the solar eclipse coordinates).

The results of computation of v_2 according to (8)-(10) on the basis of the initial data $H_{1,2}$, $\theta_{1,2}$, $\phi_{1,2}$, v_1, n_1 are presented in the table (designation of v_2*) from which it is evident that computations in 10 cases out of 11 give increases or decreases in flux velocity during passage through the discontinuity in correspondance with what was registered by the plasma detector and computed v_2* and observed v_2 values of velocity behind the front agree among themselves sufficiently well. This agreement of calculations with the experiment, i.e. that velocity of the studied discontinuities changes in the same way that it must change on rotating discontinuities, supports the proposition that 10 out of 11 discontinuities are discontinuities of the rotating type. Only for the discontinuity of 29 September at 2000 hours UT is there a divergence between the calculations and the experiment, which forces this discontinuity into the category of tangential discontinuities, as was done in [9].

Table

ч : hours , м = minutes

a) Дата Время, UT	4.VIII.1967 г. 02 ч. 51 м. a	20.IX 09 ч. 17 м. b	20.IX 22 ч. 21 м. c	29.IX 20 ч. 00 м. d	30.X 19 ч. 55 м. e	10.XI 15 ч. 42 м. f	10.XI 22 ч. 05 м. g	17.XI 05 ч. 51 м. h	6.XII 01 ч. 06 м. i	6.XII 09 ч. 00 м. j	6.XII 11 ч. 37 м. k
n_1, $см^{-3}$	2,3±1,5	1,6±0,3	2,5±0,3	1,8±0,2	1,4±1,0	1,4±0,4	2,0±1,0	2,0±0,4	4,0±1,2	3,6±0,6	4,3±0,5
n_2, $см^{-3}$	1,5±0,3	4±2	2,0±1,0	1,9±0,2	1,0±0,8	1,9±0,2	2,0±1,0	2,0±0,5	2,5±0,5	3,5±0,6	3,0±1,0
H_1, γ	4,8±0,5	11,7±0,2	10,8±0,5	7,2±0,2	3,8±0,4	4,6±0,2	5,8±0,2	5,4±0,2	7,8±0,2	8,6±0,5	9,6±0,2
H_2, γ	4,5±0,2	11,2±0,2	12,3±0,6	7,2±0,2	4,9±0,3	5,2±0,1	5,9±0,3	5,7±0,3	7,6±0,2	7,4±0,6	7,7±0,5
φ_1, град.[b]	151±10	270±4	317±10	351±5	104±10	338±10	72±5	320±10	92±10	141±5	264±10
φ_2, град.[b]	312±5	149±2	130±5	107±3	333±5	100±5	113±3	213±15	341±15	330±4	322±10
θ_1, град.[b]	29±10	—37±6	12±10	—65±10	29±8	62±10	34±5	15±15	29±4	—45±5	50±10
θ_2, град.[b]	—20±4	—31±3	(49±3)	—60±5	63±5	50±4	—20±3	47±6	56±15	15±6	—15±5
v_1, км/сек[c]	400±7	485±20	777±12	700±8	481±20	457±4	395±20	450±25	600±7	633±10	604±9
v_2, км/сек[c]	336±2	590±6	869±4	615±5	398±10	522±14	504±20	535±5	540±10	572±6	545±5
v_2^*, км/сек[c]	309	690	887	778	387	514	459	564	556	510	547
$\Delta\varphi_v$, град.[b]	12	—20	—10	—4	0	—8	0	—1	8	11	—2
$\Delta\theta_v$, град.[b]	—10	2	6	0	7	0	—10	—3	3	9	—10
φ_n, град.[b]	247	203	151	239	213	208	94	102	233	207	124
θ_n, град.[b]	22	—54	—68	+76	57	—72	8	—43	—56	+63	—14
φ_n', град.[b]	10	33	226	45	95	212	189	243	19	244	42
θ_n', град.[b]	55	—36	5	15	15	17	34	—39	—28	—15	—32

Key: a) Date and time, universal time
b) Degrees
c) Km/sec

It is interesting that the time investigated above for leaps in v_t and H_t, characteristic for rotating discontinuities is sufficiently clearly expressed qualitatively during preliminary review of the material as a dependency of the difference $\Delta v = v_2 - v_1$ on ϕ_2 (see the table and Fig. 1, with T on the figure corresponding to a tangential discontinuity). If ϕ_2 lies in the second quadrant (h is directed from the sun), Δv is greater than zero. When ϕ_2 is in the fourth quadrant (h is directed toward the sun), Δv is less than zero. We note that for tangential discontinuities, jumps in flux velocity and magnetic field are not interconnected and a probability of attaining the indicated distribution of signs for Δv according to ϕ_2 in a randomly selected series of 11 tangential discontinuities is equal to only approximately $2 \cdot 10^{-3}$.

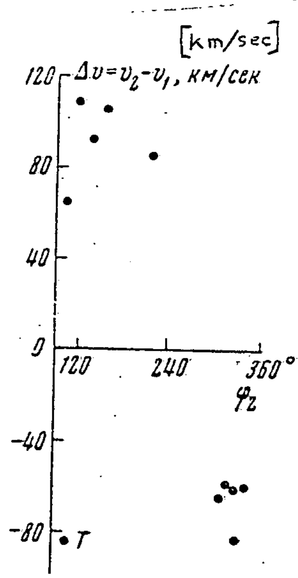

Fig. 1

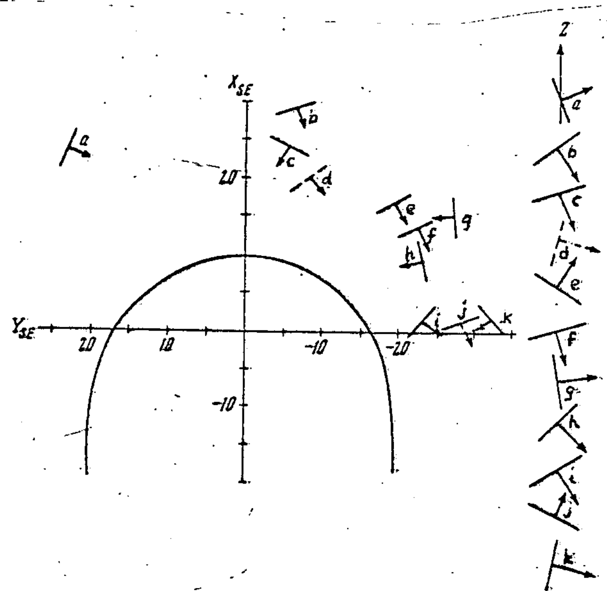

Fig. 2

Variation in the direction of flux velocity during the transfer from v_1 to v_2 may take place in a rotating discontinuity. The investigated data represents some possibility of experimental checking of this proposition. We evaluate the variations in directions v in the supposition that they are caused by rotating discontinuities (uncertainty of the knowledge of the direction of $v_{1,2}$ have little effect on these evaluations). The orientation of v_2 is approximately determined by the angles

$$\varphi_{v_2} \approx \operatorname{arc\,tg} \frac{v_1 \sin\beta + m_t \Delta v_t}{-v_1 \cos\beta + l_t \Delta v_t}, \quad \theta_{v_2} = \arcsin \frac{n_t \Delta v_t}{v_2}, \tag{11}$$

and variations in the direction of v during passage through the discontinuity

$$\Delta\varphi_v \approx \varphi_{v_2} - (180 - \beta), \ \Delta\theta_v \approx \theta_{v_2}. \tag{12}$$

The results of computations of $\Delta\phi_v$ and $\Delta\theta_v$ are presented in the table. In the experiment [9], the plasma detector allowed determination of only the location of ϕ_v at one or another azimuthal sector of widths $\Delta\phi = 22.5°$ and also the sin of the variation $\Delta\phi_v$ according to loss of the flux in one of the sectors and appearance in another, i.e. possibilities for determining the direction of v and its variations were extremely limited. With the help of such an arrangement, changes in the total of 2 discontinuities out of 11 were registered: on 6 December at 0106 hrs and 0900 hrs UT, the disappearance of the flux in sector 10 and its appearance in sector 9 were observed, which corresponds to variations $\Delta\phi_v > 0$ during passage through the discontinuity. The calculated values of $\Delta\phi_v$ of these discontinuities (table) were equal to +8 and +11°, i.e. coincided according to sign with the observed variations. For 4 discontinuities (30 October at 1955 hrs, 10 November at 2205 hrs, 17 November at 0551 hrs, 6 December at 1137 hrs) variations of $\Delta\phi_v \approx 0$ to -2, i.e. were practically not present. And finally, for the remaining discontinuities, a rather high probability existed that sin $\Delta\phi_v$ would not be registered by the detector (a change in sectors would not occur), since $\Delta\phi_v < 22.5°$. Therefore, the existent data on the direction of v and its variations agrees with the results of calculations on variations in the direction of v which were accomplished in the supposition that these variations were caused by rotating discontinuities. The methodology in determining standards for anisotropic rotating discontinuities is the same as for that determining shock waves [2]. Their orientation (corresponding cases are designated by letters in the table and Fig. 2) are essentially different from the determined [9] (ϕ_n', θ_n' in the table) in the supposition that the reviewed discontinuities are essentially tangential. Out of 10 discontinuities, 5 have the mark of an anisotropic rotating discontinuity -- the module of H changes during passage through the front by ~0.2 to 2 γ, which are outside the limits of measuring error. This property of rotating discontinuities should be considered during interpretation of solar wind discontinuities, since otherwise this problem is approached from the position of isotropic magnetohydrodynamics, which took place in [9]; identification of rotating discontinuities would be made essentially more difficult.

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